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The Evolution of Proto-Strange Stars

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1 Introduction

Since the idea that strange quark matter (SQM) may be the ground state of hadronic matter [1] it has been a topic of great interest to find ways to discern between neutron stars (NSs) and strange stars (SSs). There have been several proposals related to this idea. For example, if the transition from nuclear matter to SQM occurs during the cooling of a spin-down pulsar it may be detected as a giant glitch [2] because the star should undergo a sudden change in it moment of inertia. Another possibility is to look for differences in the cooling of young presumed NSs [3]. Also, if it were possible to measure the radius of low mass objects, we could distinguish SSs from NSs because of their smaller radius [4].

If SQM actually were the ground state of matter, several interesting astrophysical consequences should be expected. For example, there may exist high density cores inside otherwise standard white dwarf stars. If these stars undergo non-radial pulsation, the modes would be splitted on several close, detectable periods [5]. SQM formation may be the process that releases enough energy to produce the core collapse supernova explosions [6].

In the conditions present in the first seconds after core bounce, the hadronic matter that made up a *proto*-NS (PNS) contains a gas of degenerate electron neutrinos. At the very beginning the evolution of the PNS is dominated by the release of its neutrino content. It has been found that a gas of degenerate neutrinos pushes away the critical density for the transition to quark matter. Thus, PNS deleptonization *favors* the occurrence of the transition [7]. During the first minutes of the evolution of PNSs the thermodynamic conditions at their interiors change so strongly that we think this to be the best place to detect the transition to SQM. It should be remarked that supernovae light curves are absolutely insensitive to the details of the explosion. So, the only way to observe the transition to SQM (if it really occurs) is by observing the neutrino emission of a forthcoming nearby core collapse supernova. If close enough, such an event will allow the detection of a large number of neutrinos allowing for detailed statistical studies. Unfortunately, the historical detections related to SN1987A [8] were not enough for this purpose because of the low number of neutrinos.

In order to interpret future detailed neutrino observations it is relevant to have available models of the behavior of NSs during its first seconds. This has been the subject of several papers [9, 10, 11, 12]. Here we shall present the first results we have found in the evolution of bare SSs. This represents the starting point of an effort devoted to predict the details of the neutrino signal due to the transition from nuclear matter to SQM. Here we do not consider the occurrence of the transition to SQM during evolution, but center our attention on the process of deleptonization of the SSs leaving the inclusion of the physics of the quoted transition to future works.

The reminder of this paper is organized as follows: In Section 2 we describe our General Relativistic, hydrostatic stellar evolution code. In Section 3.1 we briefly describe the physical ingredients we employed and in Section 4 we present our first results. Finally, in Section 5 we make some concluding remarks.

2 Relativistic Stellar Evolution

We have adapted our Newtonian stellar evolution code [13] to solve the equations of General Relativistic, hydrostatic stellar evolution [11] in the diffusion approximation. The structure evolves with a timescale far larger than transport, thus we solve it with two coupled Henyey (finite differences, fully implicit) schemes: one for the structure and the other for the transport [11]. Initially, at the stellar interior, neutrino mean free paths are far shorter than the size of the star. However this is not the case at the outer layers or at later times. So, we adopted a flux limiter to assure that causality is fulfilled.

The fluxes of lepton number H_ν and energy F_ν are

$$H_\nu = -\frac{T^2 e^{-\Lambda-\phi}}{6\pi^2}\Big[D_2 \frac{\partial (T e^{-\phi})}{\partial r} + (T e^{-\phi}) D_3 \frac{\partial}{\partial r}\Big(\frac{\mu_e}{T}\Big)\Big], \tag{1}$$

$$F_\nu = -\frac{T^3 e^{-\Lambda-\phi}}{6\pi^2}\Big[D_3 \frac{\partial (T e^{-\phi})}{\partial r} + (T e^{-\phi}) D_4 \frac{\partial}{\partial r}\Big(\frac{\mu_e}{T}\Big)\Big] \tag{2}$$

T is the temperature, Λ and ϕ are factors appearing in the spherical Schwarszchild metrics, r is the radius and μ_e is the electron neutrino chemical potential. We consider electron, muon and tau neutrinos. In general $\mu_e \neq 0$ but muon and tau neutrinos are due to pair creation, thus $\mu_\nu = 0$, $\mu_\tau = 0$. Then, diffusion coefficients are $D_2 = D_2^{\nu_e} + D_2^{\overline{\nu}_e}$, $D_3 = D_3^{\nu_e} - D_3^{\overline{\nu}_e}$, $D_4 = D_4^{\nu_e} + D_4^{\overline{\nu}_e} + 4D_4^{\nu_\mu}$ where

$$D_n^j = \int_0^\infty dx x^n f(E_1) \, \frac{(1 - f(E_1))^2}{\sum_i (\sigma_i / V)}, \quad j = \nu_e, \overline{\nu}_e, \nu_\mu. \tag{3}$$

σ_i represent the cross section of the reactions that provide the neutrino opacity (see below) and $f(E_1) = (1 + \exp[(E_1 - \mu_1)/T]$ is the occupation number corresponding to the considered neutrino. The equation of lepton number per baryon Y_L and energy conservation are

$$\frac{\partial Y_L}{\partial t} + e^{-\phi} \frac{\partial}{\partial a}(4\pi r^2 e^{\phi} F_\nu) = 0, \tag{4}$$

$$e^{\phi} T \frac{\partial s}{\partial t} + e^{\phi} \mu_e \frac{\partial Y_L}{\partial t} + e^{-\phi} \frac{\partial}{\partial a}(4\pi r^2 e^{2\phi} H_\nu) = 0. \tag{5}$$

s is the entropy per baryon and t is the time. The equations of hydrostatic equilibrium, gravitational mass, radius, and metrics are

$$\begin{aligned}
\frac{\partial P}{\partial a} &= -\frac{e^{\Lambda}}{4\pi r^4 n_B}(\rho + P)(m + 4\pi r^3 P), \\
\frac{\partial m}{\partial a} &= \frac{\rho}{n_B e^{\Lambda}}, \\
\frac{\partial r}{\partial a} &= \frac{1}{4\pi r^2 e^{\Lambda} n_B}, \\
\frac{\partial \phi}{\partial a} &= \frac{e^{\Lambda}}{4\pi r^4 n_B}(m + 4\pi r^3 P).
\end{aligned}$$

a represents the baryon number enclosed by a sphere of radius r which is an adequate Lagrangian coordinate for our purposes, P is the pressure and n_B is the baryon number density. At the center we have $r(0) = 0$; $m(0) = 0$; $H_\nu(0) = 0$; $F_\nu(0) = 0$ whereas, at the surface $\phi(a_s) = \frac{1}{2}\log[2m(a_s)/r(a_s)]$ and $P(a_s) = P_s$. The neutrino luminosity is $L_\nu = e^{2\phi} 4\pi r^2 H_\nu$.

3 Physical Ingredients

3.1 Neutrino Opacity

Neutrino opacity has been computed following the formalism presented in Ref. [14]. As stated above, we considered electron, muon and tau neutrinos assuming that $\mu_e \neq 0$, $\mu_\nu = 0$, $\mu_\tau = 0$. We considered the cross section per unit volume given by

$$\frac{\sigma}{V} = g\int \frac{d^3p_2}{(2\pi)^3}\int \frac{d^3p_3}{(2\pi)^3}\int \frac{d^3p_4}{(2\pi)^3}\ W_{fi} f_2(1-f_3)(1-f_4)(2\pi)^4 \delta^4(p_1+p_2-p_3-p_4),$$

where the matrix element W_{fi} is

$$W_{fi} = \frac{G_F^2}{E_1E_2E_3E_4}\Big[(\mathcal{V}+\mathcal{A})^2(p_1\cdot p_2)(p_3\cdot p_4) + (\mathcal{V}-\mathcal{A})^2(p_1\cdot p_4)(p_3\cdot p_2) - (\mathcal{V}^2-\mathcal{A}^2)(p_1\cdot p_3)(p_4\cdot p_2)\Big].$$

E_i and p_i are the energy and momentum of each particle participating in the reactions (e.g., $\nu_e + d \to e^- + u$, $i = 1, 2, 3, 4$ respectively). $\mathcal{V}$ and $\mathcal{A}$ are coefficients corresponding to each reaction, given in [14], and the other symbols have their standard meaning. We have developed a Montecarlo integration scheme that provides the quark matter neutrino opacity for the thermodynamic conditions relevant at SS interiors.

3.2 Equation of State

For the equation of state of the SQM we have adopted the standard description provided by the MIT bag model. In the zero strange quark mass limit, it is well known that the form of the equation is $P = \frac{1}{3}(\rho - 4B)$, with B a constant that parametrizes the non-perturbative interactions giving rise to confinement. In the simulations presented below we adopted the "standard" value of $B = 60MeV fm^{-3}$. When a finite value for the quark mass is employed there are deviations from the simple form given above, although the linearity still holds to a high degree.

4 Results

We have applied our new relativistic stellar code to the case of a 1.4 $M_\odot$ homogeneous proto SS. We considered an initial energy content compatible with that expected for a gravitational collapse of a massive star. The evolution of the temperature and the neutrino abundance per baryon of this object is depicted in Fig. 1.

The proto SS is initially hot and plenty of neutrinos that tend to diffuse outwards on a timescale of tens of seconds. The net leptonic number carried by neutrinos is lost in the process termed "deleptonization" in the literature. Heat (mainly in neutrino pairs) takes a much longer timescale, as indicated by the comparison of both panels

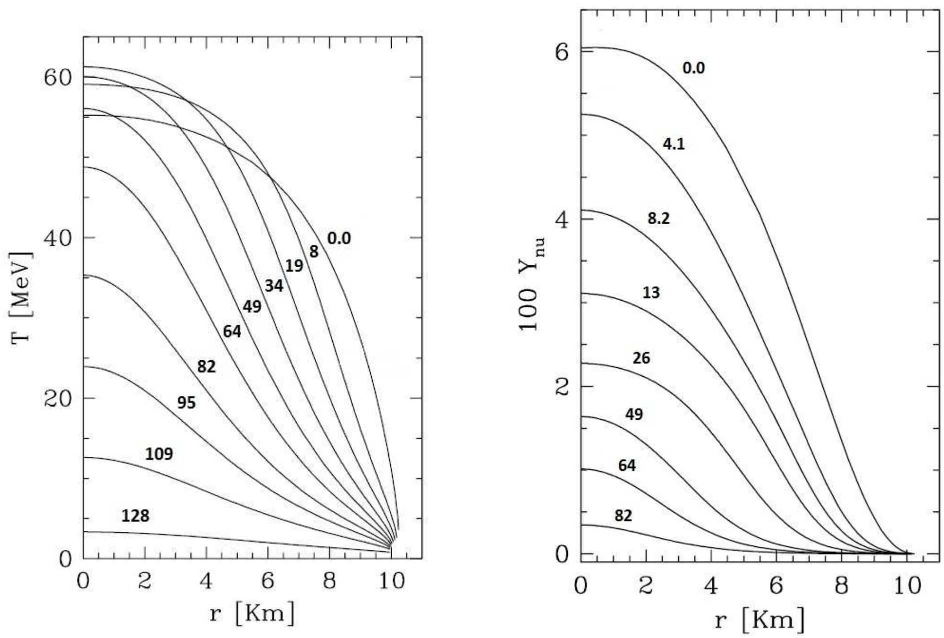

Figure 1: Left panel: The temperature profile during the first seconds of evolution of a 1.4 $M_\odot$ homogeneous SS. Each curve is labeled with its age, given in seconds on the right. Notice that, due to the outgoing neutrino flux at the fist stages of evolution the inner layers of the star get hotter (Joule effect). Right panel: The neutrino per baryon profile of the same SS. Notice that the timescale of deleptonization is appreciably shorter than that of cooling.

of Fig. 1. Because the SS interior is strongly degenerate, the star also undergoes a tiny contraction. In fact the gravitational mass and radius evolve less than in the case of NSs, in which the outer layers are partially degenerate and more sensitive to thermal effects.

In is interesting to compare these results with the Fig. 9 of Ref. [11]. Our calculations indicate that NSs undergo a much faster evolution as compared to SSs. Certainly, this is important in predicting the neutrino signal of the phase transition to SQM and also in interpreting the observed signal in SN1987A within these models.

5 Conclusions

In this conference we have presented the first results of the evolution of a 1D, bare, proto SSs. This represents a starting point in our effort devoted to predict the neutrino signal to be expected to arrive from the next nearby core collapse supernova. Recent work has explored 2D simulations in which the acceleration of the conversion front on its way outwards could be addressed [15], although several open questions remain in both type of modeling and their eventual consistency. We have performed a detailed computation of the neutrino opacity and coupled it to a flux limited, hydrostatic, General Relativistic stellar evolution code. Then, we applied the code to the evolution of a 1.4 $M_{\odot}$ homogeneous SS finding a slower evolution as compared to standard PNS evolution. The net lepton number is lost faster than the thermal energy, and it may be expected that the signal in a neutrino detector should last longer. However, a closer inspection to the Fig. 1 also shows that the temperature of the neutrinosphere (the imaginary surface at which most of the neutrinos freely escape) decreases a factor ~ 2 in the first $\sim 10 sec$, causing the mean energy of the emitted neutrinos to fall below $\sim 5 MeV$ or so. Thus, the emission of the leaking neutrinos stands, but they are less energetic and easily missed unless the threshold of the detector is very low. This and other important features should be studied in depth and a more detailed description of the results is in preparation and will be published elsewhere.

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